# Heavy Flavour Physics at CDF

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**Abstract.** We present recent CDF measurements of mass, lifetime and CP violation properties of B hadrons. The analyzes presented in this paper use up to 2.8 fb$^{-1}$ of data. CDF has already accumulated close to 5 fb$^{-1}$ of data which promises significant improvements of these analyzes in the near future.

## 1. Introduction

We present recent Heavy Flavour Physics results from the CDF experiment [1] which has accumulated 5 fb$^{-1}$ of data. The measurements presented in this paper make use of up to 2.8 fb$^{-1}$ of data. We summarize results of the $B_c$ mass and lifetime, $\Lambda_b$ and $B_s$ lifetimes measured for the first time from samples selected by a trigger which requires the presence of tracks with large impact parameter with respect to the primary vertex and CP violation in $B_s \to J/\psi\phi$ decays.

## 2. Mass and Lifetime of the $B_c$ Meson

The $B_c$ meson is unique as it contains two heavy quarks: $b$ (bottom) and $\bar{c}$ (anti-charm). The most precise measurement of the $B_c$ mass was recently performed by the CDF experiment with 2.4 fb$^{-1}$ of data [2] using the fully reconstructed decay mode $B_c^+ \to J/\psi[\to \mu^+\mu^-]\pi^+$. The advantage of using fully reconstructed decays is that the mass of the decaying particle can be measured precisely by fitting the invariant mass distribution. The total $B_c$ signal yield is estimated to $108 \pm 15$ candidates with a statistical significance of 8 standard deviations. The measured mass is $6275.6 \pm 2.9(stat.) \pm 2.5(syst.)$ MeV/c$^2$ which is good agreement with the corresponding D0 measurement [3] and with theoretical models which predict the $B_c$ mass around 6.3 GeV/c$^2$ [4].

The lifetime of the $B_c$ meson is measured by the CDF experiment using partially reconstructed $B_c \to J/\psi[\to \mu^+\mu^-]\, l\, \nu\, X$ decays [5] in 1.0 fb$^{-1}$ of data. Measurements are performed separately in $J/\psi\, e$ and $J/\psi\, \mu$ channels. The corresponding lifetimes are: $c\tau_\mu = 179.1^{+32.6}_{-27.2}(stat.)$ and $c\tau_e = 121.7^{+18.0}_{-16.3}(stat.)\,\mu$m. The main sources of systematic uncertainties come from our understanding of the decay time resolution function and from relative fractions of $b\bar{b}$ production mechanisms in simulation. The total systematic uncertainty is $5.5\,\mu$m, leading to a combined measurement of the $B_c$ lifetime of $c\tau_\mu = 142.5^{+15.8}_{-14.8}(stat.) \pm 5.5(syst.)\,\mu$m. This agrees well with a similar recent measurement performed by the D0 experiment [6] in the $B_c \to J/\psi\mu\,\nu\,X$ channel and with theoretical predictions [7].

## 3. Lifetime of the $\Lambda_b$ Baryon

The lifetime of the $\Lambda_b$ baryon was measured for the first time in a fully hadronic decay mode, $\Lambda_b^0 \to \Lambda_c^+[\to p^+K^-\pi^+]\pi^-$, by the CDF experiment. This was made possible by using a trigger which selects events with two tracks with large impact parameter $(d_0)$ with respect to the primary vertex, $d_0 > 120\mu$m. The large impact parameter of secondary vertex tracks is characteristic to long lived $b$ hadrons like $\Lambda_b$ and it is a powerful discriminant against prompt background. This analysis uses 1.1 fb$^{-1}$ of data in which a total of 3000 signal $\Lambda_b$ events are found after signal to background optimization. The invariant $\Lambda_b$ mass and decay time distributions are shown in Fig 1. Because the sample is selected by a trigger which requires displaced tracks,
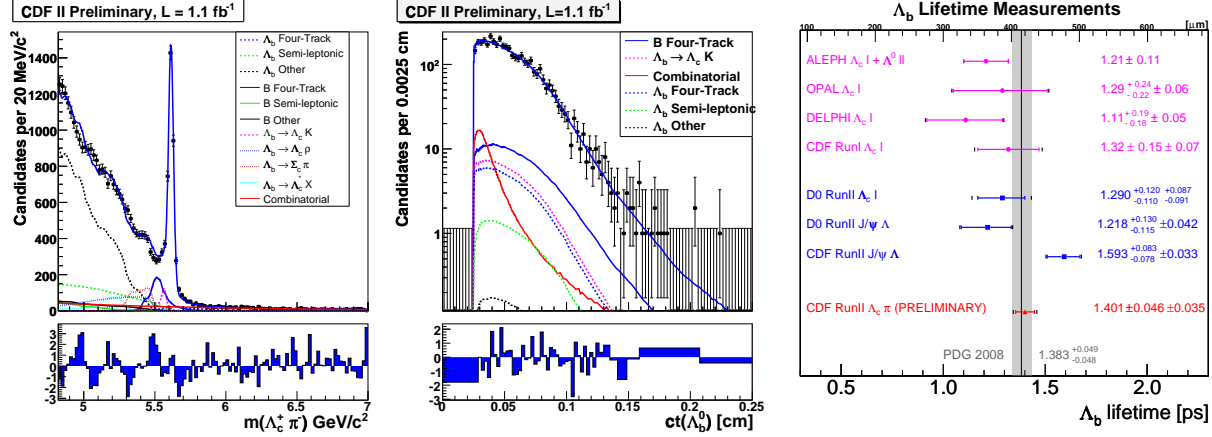


**Figure 1.** Invariant $\Lambda_c\pi$ mass (left) and $\Lambda_b$ decay time (center) distributions with fit projections superimposed. Comparison between different $\Lambda_b$ lifetime measurements and the current world average (right).

events with low decay time are suppressed. The trigger efficiency is determined from simulation and used in the maximum likelihood fit to correct for this effect. The measured lifetime is [8] $c\tau(\Lambda_b) = 420.1 \pm 13.7(stat.) \pm 10.6(syst.)\mu$m. The main systematic uncertainty comes from our limited knowledge the trigger efficiency simulation. The ratio between the $\Lambda_b$ lifetime measured in this analysis and the $B^0$ world average lifetime [9] is $0.922 \pm 0.039$ which is in good agreement with theoretical calculations [10] which predict a ratio of $0.88 \pm 0.05$ and with previous results summarized in Fig. 1.

## 4. Lifetime of the $B_s$ Meson

The CDF experiment has performed for the first time a measurement of the $B_s$ lifetime in fully hadronic $B_s^0 \to D_s^-[\to \phi\pi^-]\pi^+$ decays, where $\phi \to K^+K^-$. Since the $B_s$ flavor ($B_s$ or $\bar{B}_s$) can be inferred from the decay products, this decay mode is refereed to as flavor specific. The analysis also includes partially reconstructed decays like $B_s \to D_s^-\rho^+[\to \pi^+\pi^0]$ where the $\pi^0$ from the $\rho$ decay is not reconstructed. This analysis uses 1.3 fb$^{-1}$ of data which was collected by the same displaced track trigger used for the $\Lambda_b$ lifetime measurement described in the previous section. A similar trigger bias correction is applied. After signal to background optimization the sample yields 1100 fully reconstructed $B_s$ decays and about twice as many partially reconstructed $B_s$ decays. The $D_s\pi$ invariant mass distribution is shown in Fig 2. The measurement procedure is tested on larger control samples of $B^0 \to D^-\pi^+$, $B^0 \to D^{*-}\pi^+$ and $B^+ \to \bar{D}^0\pi^+$ decays, where the $B^+$ and $B^0$ lifetimes are measured in good agreement with the world averages [9]. This analysis [11] yields the best $B_s$ lifetime in flavor specific decays
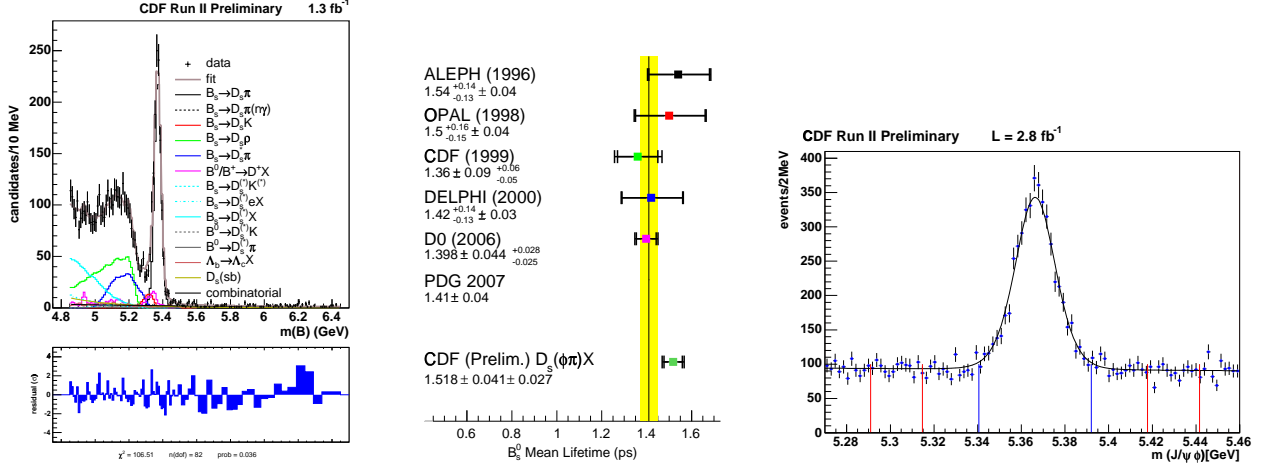
**Figure 2.** Invariant $D_s\pi$ mass distribution with fit projections superimposed (left). Comparison between the recent CDF $B_s$ lifetime measurement and previous measurements (center). Invariant $J/\psi\phi$ mass distribution with fit projection superimposed (right).

$\tau(B_s) = 1.518 \pm 0.041(stat.) \pm 0.025(syst.)$. As in the case of the $\Lambda_b$ lifetime measurement, the largest systematic uncertainty comes from the limited understanding of the trigger simulation. The $B_s$ lifetime measured in this analysis is larger than the previous world average as seen in Fig 2. This new result will push the previous world average ratio between the $B_s$ lifetime and the $B^0$ lifetime ($0.94 \pm 0.02$) to a larger value, closer to the Heavy Quark Effective Theory [12] prediction of $1.0 \pm 0.02$.

## 5. CP Violation in $B_s \to J/\psi\phi$ Decays

A meson with $B_s^0$ flavor at production time can have the same flavor $B_s^0$ at decay time or it can decay from an oscillated $\bar{B}_s^0$ state. This is possible because $B_s^0$ and $\bar{B}_s^0$ mesons oscillate from one another with high frequency. The relative phase between the two possible decay amplitudes, $\beta_s = \arg\left(-\frac{V_{ts}V_{TB}^*}{V_{cs}V_{cb}^*}\right)$ is responsible for CP violation in $B_s \to J/\psi\phi$ decays. In the Standard Model (SM) this phase is predicted to be very small $O(\lambda^2) \approx 0.02$ [13]. Although the final state in this decay, $J/\psi[\to \mu^+\mu^-]\phi[\to K^+K^-]$, is not a CP eigenstate, it is however a superposition of CP eigenstates. Since both $J/\psi$ and $\phi$ are spin 1 particles, the final state $J/\psi\phi$ has total angular momentum of either 0, 1 or 2. The states with angular momentum 0 and 2 are CP even while the state with angular momentum 1 is CP odd. The CP even and CP odd eigenstates can be statistically separated by doing an angular analysis of the final decay products $\mu^+\mu^-$ and $K^+K^-$. Both same side and opposite side flavor tagging techniques are used to separate $B_s^0$ from $\bar{B}_s^0$ production flavors.

The CDF experiment has performed a study [14] of CP violation in $B_s \to J/\psi\phi$ decays using 2.8 fb$^{-1}$ of data selected by a di-muon trigger. After signal optimization the sample contains about 3200 $B_s \to J/\psi\phi$ signal events as seen in Fig 2. The measured average $B_s$ lifetime is $1.53\pm0.04(stat.)\pm0.01(syst.)$ ps. Assuming no CP violation the decay width difference between the heavy and light $B_s$ mass eigenstates is determined $\Delta\Gamma_s = 0.02\pm0.05(stat.)\pm0.01(syst.)$ ps$^{-1}$. When allowing for CP violation in the maximum likelihood fit, non-Gaussian effects are accounted for by using a frequentist approach for determining two dimensional confidence regions in the $\beta_s - \Delta\Gamma_s$ plane. These confidence regions are shown in Fig. 3. This analysis provides strong indication that negative values of the CP violation phase $\beta_s$ are suppressed.
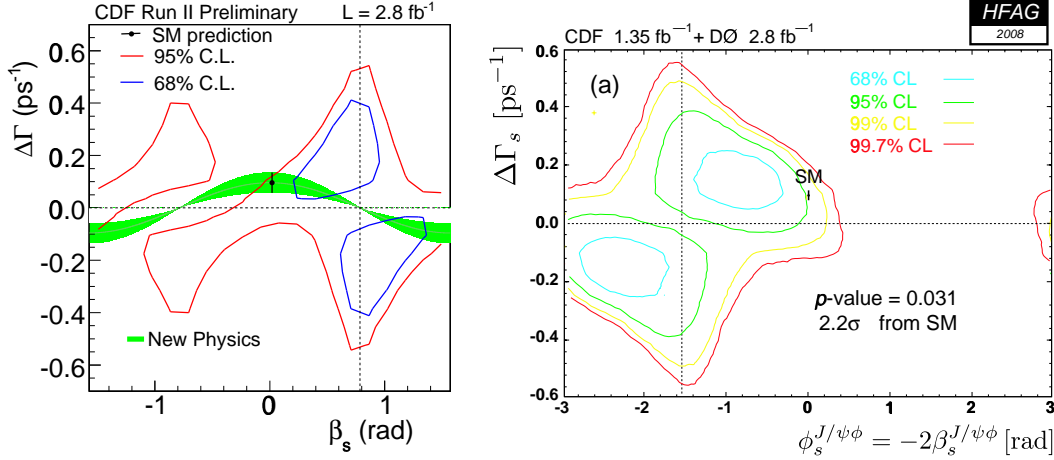
**Figure 3.** Confidence regions in the $\beta_s^{J/\psi\,\phi} - \Delta\Gamma_s$ plane from CDF (left) and in the $\phi_s^{J/\psi\,\phi} - \Delta\Gamma_s$ plane from combined CDF and D0 datasets (right). Note the definition $\phi_s^{J/\psi\,\phi} = -2\beta_s^{J/\psi\,\phi}$.

The agreement with the $\beta_s$ and $\Delta\Gamma_s$ SM prediction [13] is 7% or 1.8 standard deviations. A similar masurement carried out by the D0 experiment [16] leads to similar conclusions: negative values of $\beta_s^{J/\psi\,\phi}$ are disfavoured while the agreement with the SM expectation is 1.7 standard deviations. A combination of an older CDF measurement [15] and the D0 measurement [16] has been performed by the Heavy Flavor Averaging Group [17]. The combined confidence regions are shown in Fig. 3. The agreement with the SM prediction is at the 3% level or 2.2 standard deviations. It will be interesting to see the evolution of these results as the Tevatron experiments are expected to accumulate between 6 and 8 fb$^{-1}$ by the end of Run 2.

## 6. Conclusions
The CDF experiment has a very rich B Physics program which is complementary to, and in some aspects competitive with the B factories. Some of the best measurements of the $B_c$, $\Lambda_b$ and $B_s$ hadron properties. Updated analyzes will follow as CDF is expected to accumulate 6 to 8 fb$^{-1}$ of data by the end of the Tevatron running.

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